

RADIATION AND TEMPERATURE EFFECTS ON LDEF FIBER OPTIC SAMPLES

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SUMMARY

This paper will concentrate on results obtained from the JPL Fiber Optics LDEF Experiment since the June 1991 Experimenters' Workshop. Radiation darkening of laboratory control samples and the subsequent annealing was measured in the laboratory for the control samples. The long-time residual loss was compared to the LDEF flight samples and found to be in agreement. The results of laboratory temperature tests on the flight samples, extending over a period of about nine years, including the pre-flight and post-flight analysis periods, are described. The temperature response of the different cable samples varies widely, and appears in two samples to be affected by polymer aging. Conclusions to date are summarized.

1. INTRODUCTION

This paper presents results from the JPL fiber optic LDEF experiment obtained since the last LDEF symposium in June 1991. These results relate, first, to laboratory measurements of radiation-induced loss in control samples and the recovery of this loss with time. The test data was compared to the already measured loss increment in the LDEF flight samples, with the purpose of determining whether the short-term lab tests could be used to correctly estimate the loss accumulated in a much longer orbital mission. Secondly, additional temperature testing of both the flight samples and controls has indicated the possibility of long-term changes in temperature-induced loss due to the orbital exposure, as well as large differences in the magnitude of this effect between different types of fiber optic cables.

Post-flight fiber optic loss measurements, spectral loss measurements, temperature effects, and micrometeoroid impact experience were described in a paper presented at the first LDEF Post Retrieval Symposium (ref. 1). This paper supplements the earlier one, and extends some of the information found there.

The LDEF carried a number of fiber optic experiments (ref. 2). The length of the orbital exposure, over 5 1/2 years, and the fact that experimenters were able to recover samples and examine them in the laboratory are unique. In our experiment, the duration of the exposure to ionizing radiation, although admittedly at a low level, provides a considerably longer time base than any prior laboratory experiments (For example, see refs. 3, 4.) for examining the effects of annealing on radiation damage. In addition, no attempt has been made in other laboratory work to simulate realistically the combination of environments, including radiation, temperature, and vacuum found in an orbital spacecraft, and it would be very difficult to do so.

In the next section, our short-term radiation and annealing measurements are described, as well as the simple model used to extrapolate data taken over a 2 day period to much longer times. The following section, Section 3, contains a summary of temperature cycling measurements and briefly describes the change in temperature response observed on one flight sample. The following section describes an analysis of contamination found on one connector termination, and finally, the conclusions to date from our post-flight data analysis are presented.

2. LONG TERM RADIATION DAMAGE

Description of Fiber Cable Samples

Our LDEF flight experiment contained four fiber optic cable samples arranged in planar coils on the outer surface of the experiment tray, thus exposing them to space over one hemisphere. The samples were terminated in connectors which were held by brackets underneath the supporting plate. The external samples experienced approximately 1 krad total mission dose, calculated from dose vs shielding depth curves given by Benton and Heinrich (ref. 5). This dose is at the fiber; the dose incident on the cable jacket was at least one order of magnitude larger. Although the dose rate was not uniform over one orbit, on average it accumulated at an approximately constant rate during the 5.7 year mission. The external samples by design experienced quite a large temperature swing during each orbit, roughly 50° to 60° C each cycle, and from about -60° to +80° C extremes over the entire mission.

In addition, six internal samples, each in the form of a multiturn coil, were mounted to the bottom surface of the tray with cable ties. They were terminated in connectors also mounted in brackets. Shielding by the aluminum cover plates reduced the dose to these samples to approximately 200-300 rads. The temperature environment of the internal samples was benign, remaining near room temperature. None of the samples were cold, so annealing of the radiation damage was not arrested. No photobleaching was expected, and none was observed.

Similar terminated control samples were prepared from the same cable lot that was used for each flight sample. The control samples were stored in a laboratory environment for the duration of the mission and were used for comparison measurements of the flight sample loss after recovery and before the current radiation tests were begun. These loss measurements were already summarized in our earlier LDEF Symposium paper (ref. 1) and were presumed to be caused by the exposure to radiation during the flight, an issue that will be mentioned again later in this paper.

Laboratory Radiation Damage Measurements

Each control sample was exposed to a Co⁶⁰ gamma-ray source for approximately 260 seconds to produce a dose of 2.0 krads. In order to observe the recovery of the initial radiation - induced loss as a function of time, the tests followed procedures for transient radiation testing of optical fibers that are described in the literature (ref. 6). However, the duration of the radiation exposure from the Co⁶⁰ source was much longer than in the recommended test procedure, a minor difference because our interest was in the long-term residual loss increment.

The sample coil was aligned with its axis projecting through the source so the entire circumference of the coil was at the same distance from the source. The dose was measured at points adjacent to and within the coil to determine the average dose seen by the sample.

The loss was measured for each control sample as a function of time, the data beginning before the exposure and extending for approximately 2.5 days after exposure. Changes were recorded with respect to the pre-exposure transmission. The time scale was measured from the mid-point of the approximately 4 minute radiation exposure period.

The results for control sample P-1 are shown in Figure 1. The measurement accuracy in terms of db/km was limited by the stability of the recording system, which is estimated to be about .01 to .02 db, because the sample length was quite short. The disturbance at about 1.5×10^5 sec was a result of temperature changes in the radiation vault caused by personnel entering to conduct other unrelated tests that particular weekend.

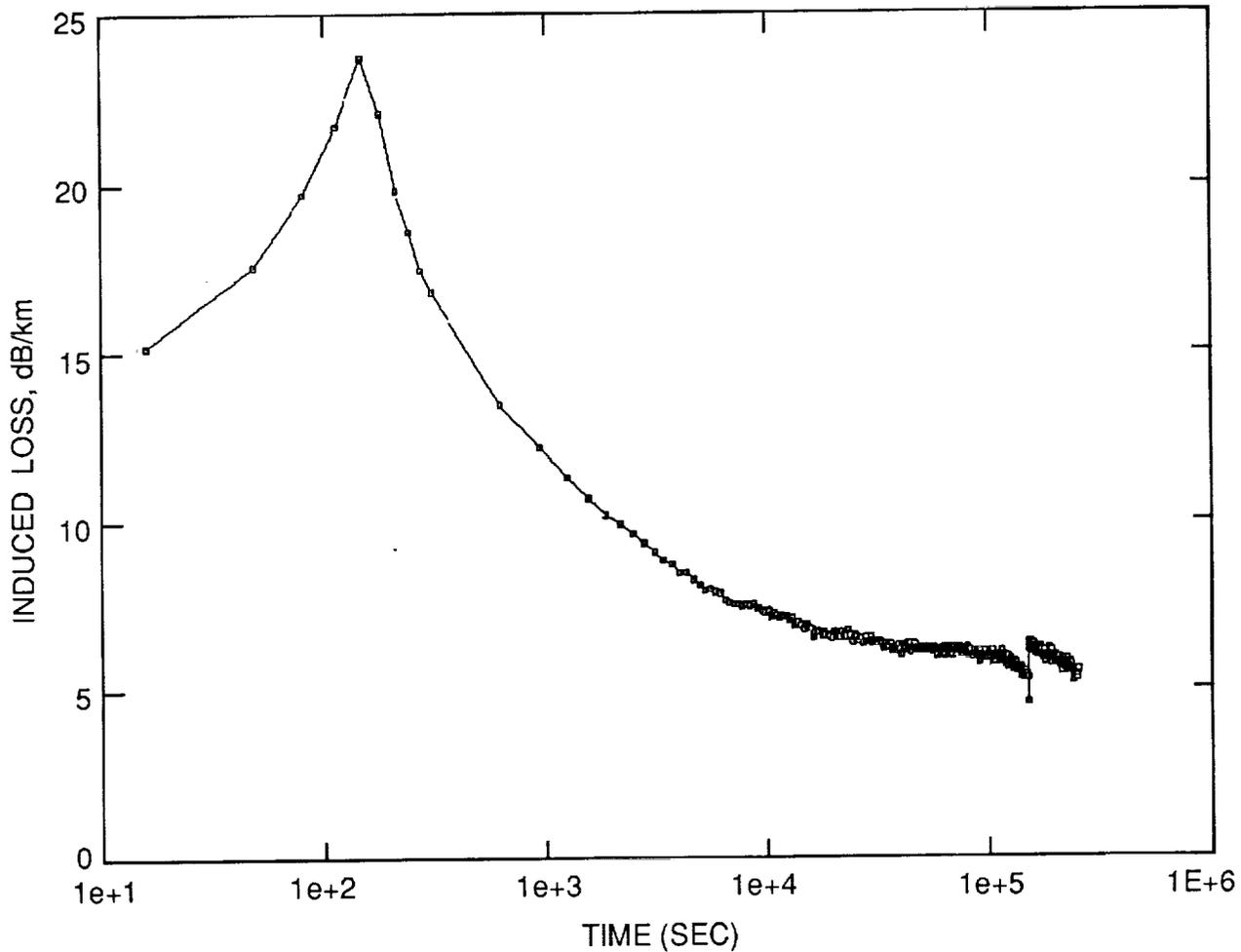


Figure 1. Transient radiation-induced loss control sample P-1. The total dose was 2.0 krad.

Sample P-1 was a 100/140 um core/clad diameter fiber with a partially graded germanium doped core and a pure fused silica cladding. There was a small amount of phosphorus added along the axis of the core to improve manufacturability. The P-1 fiber was very similar to a Corning type 1508.

Results for the same test for control sample C-1 are shown in Figure 2. Sample C-1 was a 50/125 um core/cladding diameter graded index fiber with a germanium doped fused silica core. The core was doped throughout with phosphorus, which strongly inhibits annealing of the initial damage and results in a much higher residual loss. The data points beyond about 2×10^5 sec were obtained by a direct measurement of attenuation, described in our earlier paper (ref. 2) after removing the sample from the

radiation exposure setup. No adjustment was made to fit these measurements to the in-situ data. We do not have an explanation for the observed increase in loss during the first 3-4 hrs; other samples also exhibited this characteristic. However our estimate of the long-term residual loss was not significantly affected by the initial rise.

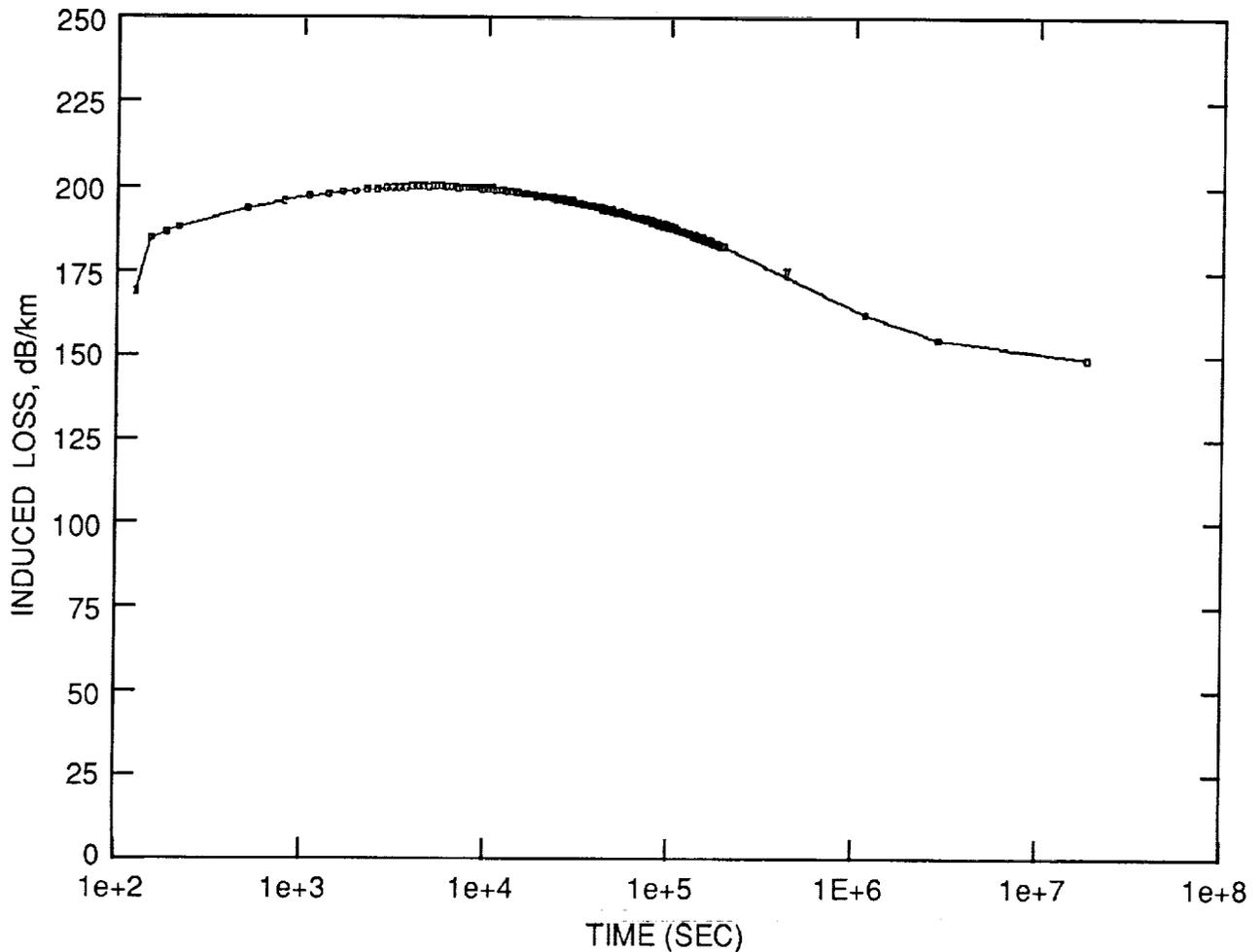


Figure 2. Transient radiation-induced loss for control sample C-1. The total dose was 2.0 krad.

Extrapolation to Long Time

Friebele (ref. 7) suggests, on very general grounds related to chemical reaction kinetics, that the recovery of radiation-induced loss can be described by the expression:

$$A(t) = (A_o - A_f) \left[1 + \frac{t}{\tau} (2^{(n-1)} - 1) \right]^{-\frac{1}{n-1}} + A_f$$

where $A(t)$ is the time-dependent radiation-induced loss following a short radiation exposure, A_o and A_f are the initial and final loss increments, and τ is a time constant. The index n is an adjustable parameter representing the order of the reaction kinetics. It is typically 2 for pure fused silica and can be as large as 5 or 10 for doped cores.

The expression above was used to estimate the long-time limit of the induced loss from the data shown in Figures 1 and 2, as well as from similar data for the other three externally mounted samples. The results are summarized in Table 1. In the table, the specific induced loss from flight data is calculated from our observed loss increment for the flight samples, converted into db/km-krad. The specific induced loss from our lab data are the results from the laboratory exposures just described. The single value from the literature was given by Friebele (ref. 8) for Corning type 1809.

Table 1. Comparison of Flight and Laboratory Radiation Damage

	P-1	P-2	P-3	P-4	C-1
Fiber type	100-140μm graded	100-140μm step	200μ PCS step	50-125μm graded	50-125μm graded
Material	Ge doped core	---	silica core	silica-borosilicate	Ge-doped core
LDEF flight dose estimate	1.0 krad	0.9	1.3	1.0	0.2
Specific induced loss from flight data	<4 db/km krad	70 ± 5	110 ± 5	95 ± 5	50 ± 10
Specific induced loss from our lab data	3 ± 1 db/km-krad	27 ± 5	72 ± 10	75 ± 7	64 ± 2
Specific induced loss estimated from published data (1)	1.7 db/km krad	---	---	---	---

(1) E.J. Friebele (ref.3)

The agreement is quite satisfactory. In the case of sample P-1, the resolution is limited by the sample length and the relatively small loss increment. Within the estimated measurement accuracy, the data agree, except for sample P-2. There is some indication that the loss increase of the other flight samples is somewhat larger than predicted by the short-term radiation tests, but the difference is not significant.

However, sample P-2 showed considerably more loss increase for the flight sample than for the lab test. It should be noted that flight sample P-2 is the one discussed in the following section because it exhibited an increase in temperature-induced loss between pre-flight and post-flight tests. There may have been changes in the properties of the buffering or cabling polymers as a result of the space exposure which caused an increase in room-temperature loss, as well as an increase in the loss increment occurring as a result of temperature change.

3. LONG-TERM CHANGE IN TEMPERATURE EFFECTS

In this section we present the results of a series of temperature tests for one of the flight samples. These tests were distributed over a long period of time, extending from pre-flight, in 1983, to 1991. Similar results are also given for a sample that showed good performance for comparison.

Description of the Temperature Tests

Typically, fiber cables suffer increased loss as their temperature decreases. The cause is the large difference in thermal expansivity between the fused silica optical fiber and the polymers used in the buffer layers and in the cable structure, which causes microbending. The magnitude of the temperature-induced loss varies over a wide range, depending on cable design.

Our LDEF experiment was passive, with no measurements being taken during the flight. However, the temperature induced loss was measured for the flight samples before launch and a number of times (at least twice) after recovery. The control samples were also tested during the post-flight period for comparison.

Figure 3 shows the result of the most recent temperature cycling test for flight sample P-1. The temperature was cycled between +70° C and -55° C three times. Each cycle was 230 minutes in length, with the temperature holding 20 minutes at each extreme and changing at a fixed rate between. The complete test took about 12 hours.

This sample had the best temperature performance of the ten LDEF samples. The fiber was coated with a UV cured acrylate buffer consisting of two layers, the inner layer with a low (Young's) modulus, and the outer with a higher modulus (ref. 9). The two layers had an outer diameter of 0.5 mm, and were contained in a hytrel tube with 0.5 mm inside diameter and 1.0 outside diameter. The entire structure was a tight fill, not loose tube, construction (footnote 1).

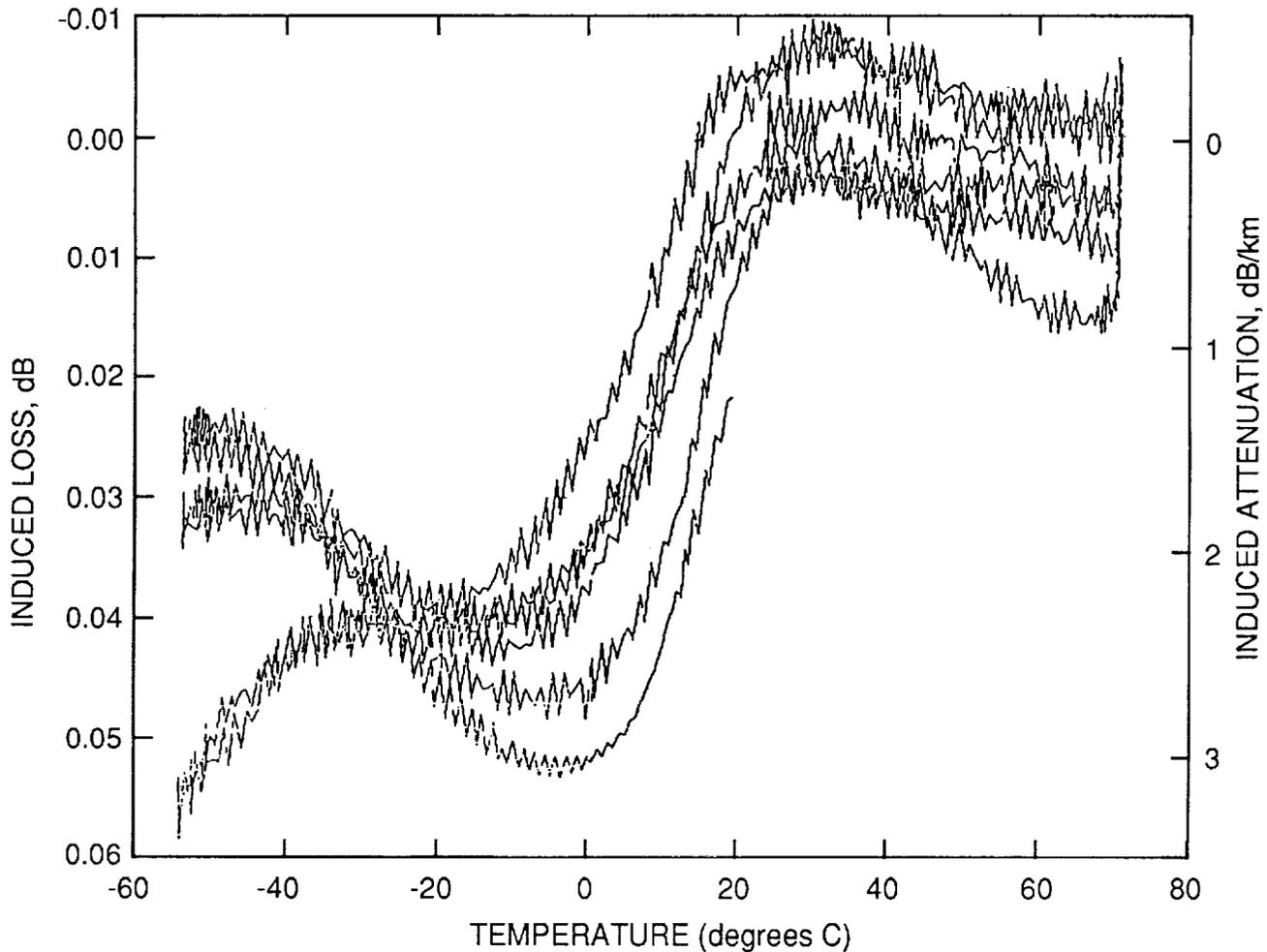


Figure 3. Temperature-induced loss for a temperature cycling test of flight sample P-1.

The total change in loss due to temperature change was 0.045 db for the sample, or 1.7 db/km over the -55°C to $+70^{\circ}\text{C}$ temperature range. The instrumental stability was about 0.01 db or 0.4 db/km. However, we feel that the data reaching -0.055 db near one low temperature extreme was caused by other activity nearby which changed the ambient laboratory temperature and should be disregarded. This performance was notably better than the average temperature induced loss of all the samples, which was about 1.5 db, or 30 db/km and also significantly better than the next-best performer, at 0.5 db, or 11 db/km.

The results shown in Figure 3 were obtained after the flight exposure and after a number of cycling tests in the laboratory, the total time of observation covering nearly nine years. There is no indication of growth in the temperature-induced loss increment for this sample.

Results for Sample P-2

Figures 4 thru 7 show the temperature-induced loss for sample P-2. Figure 4 shows the result of a pre-flight test, made in March 1983. Figure 5 is data obtained after the flight, in February 1991, for the control sample. Figure 6 shows a post-flight single cycle test made in early 1991 of the flight sample and Figure 7 shows data from a multi-cycle test made in September 1991.

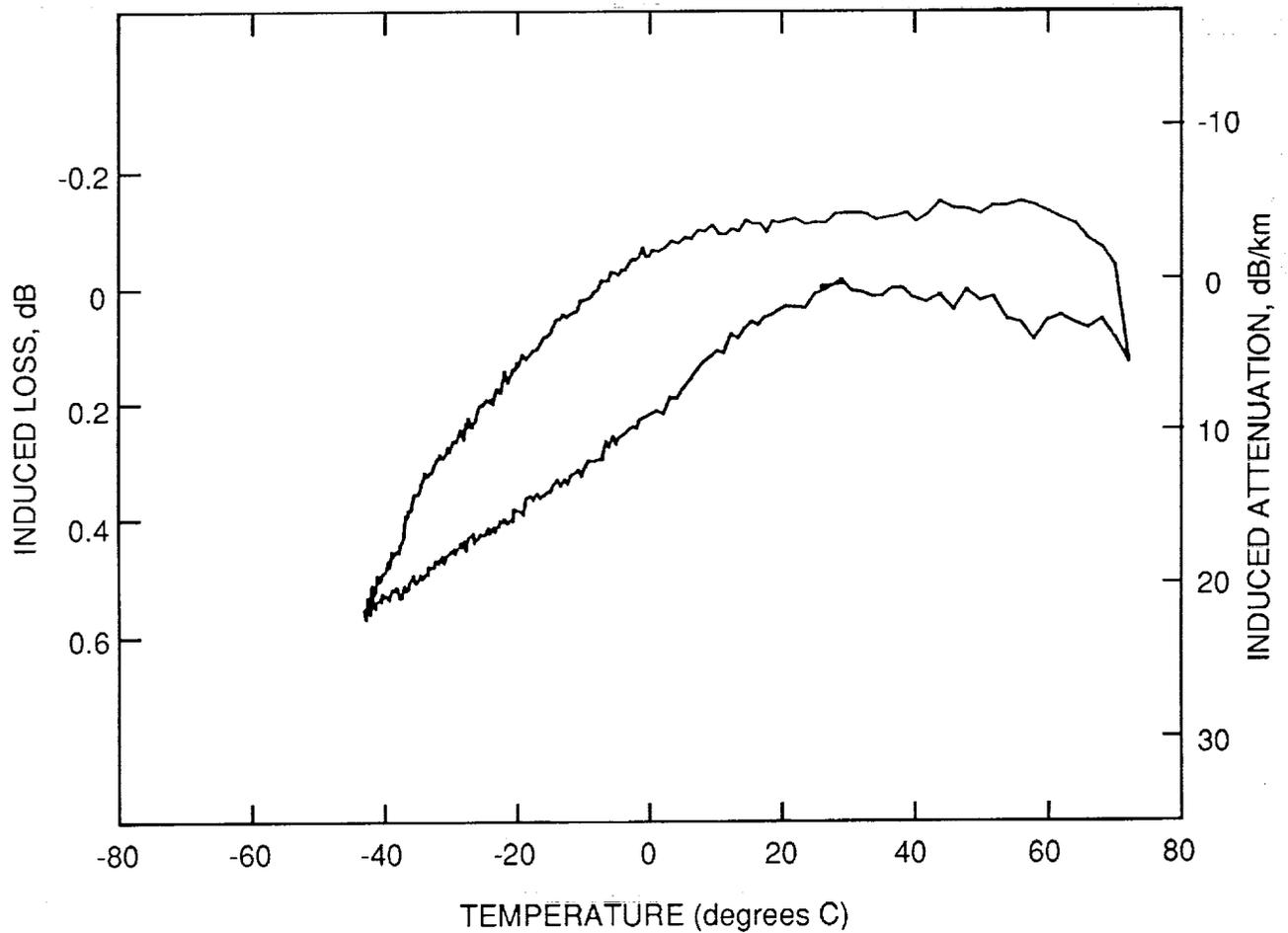


Figure 4. Temperature-induced loss for flight sample P-2 measured before the flight, in March 1983.

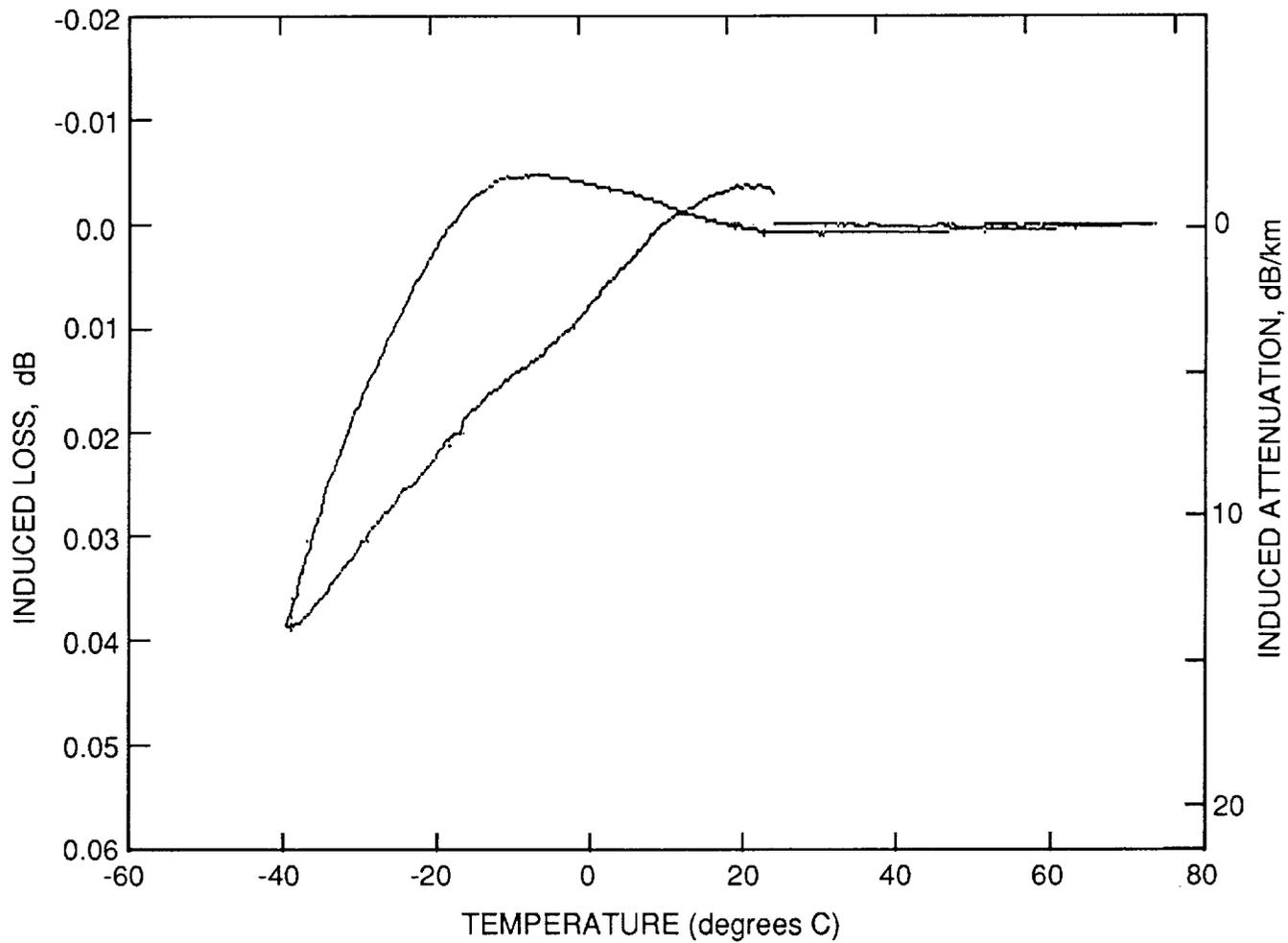


Figure 5. Temperature-induced loss for control sample P-2, measured post-flight, in February 1991.

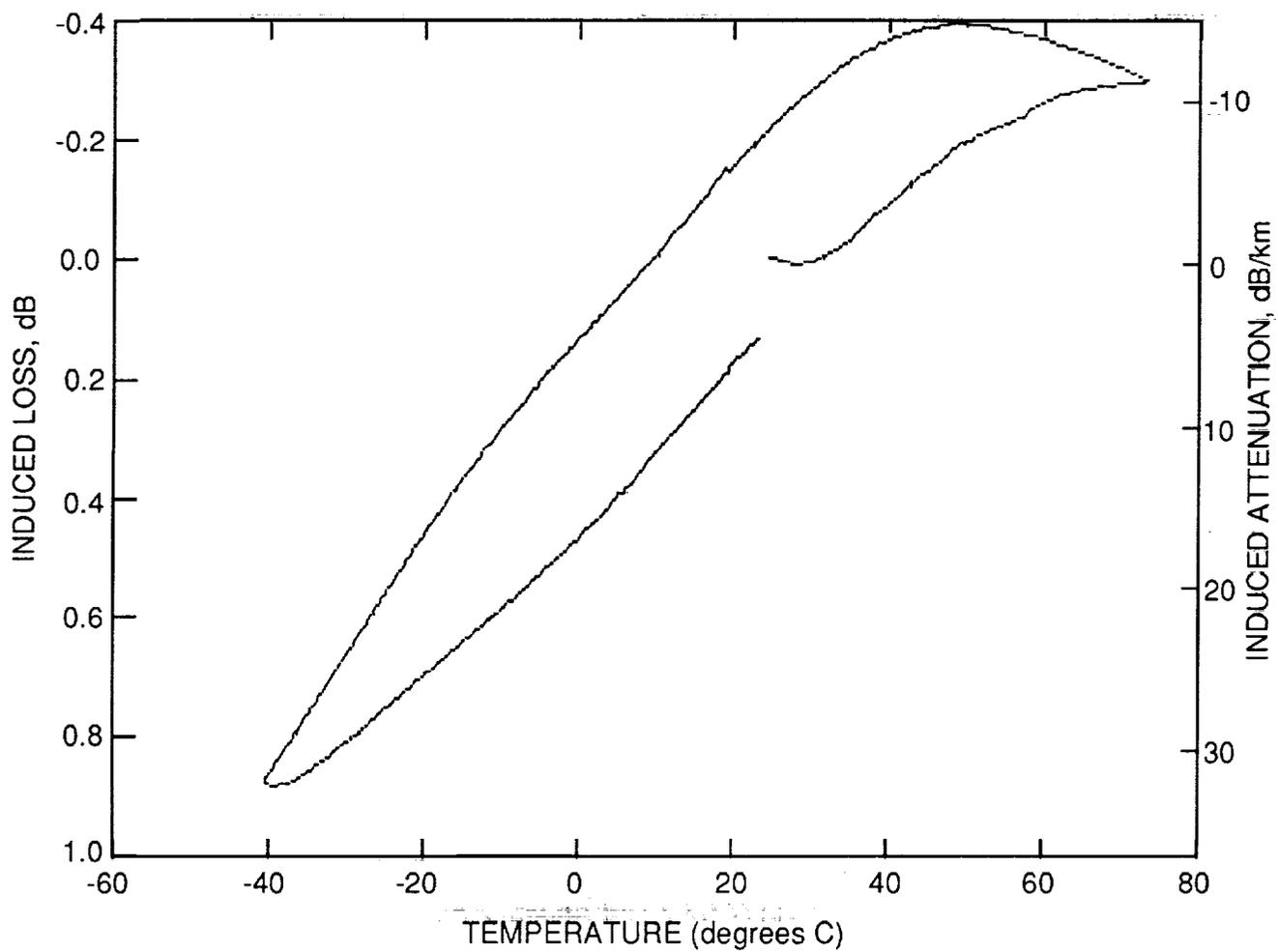


Figure 6. Temperature-induced loss for flight sample P-2, measured post-flight, in April 1991.

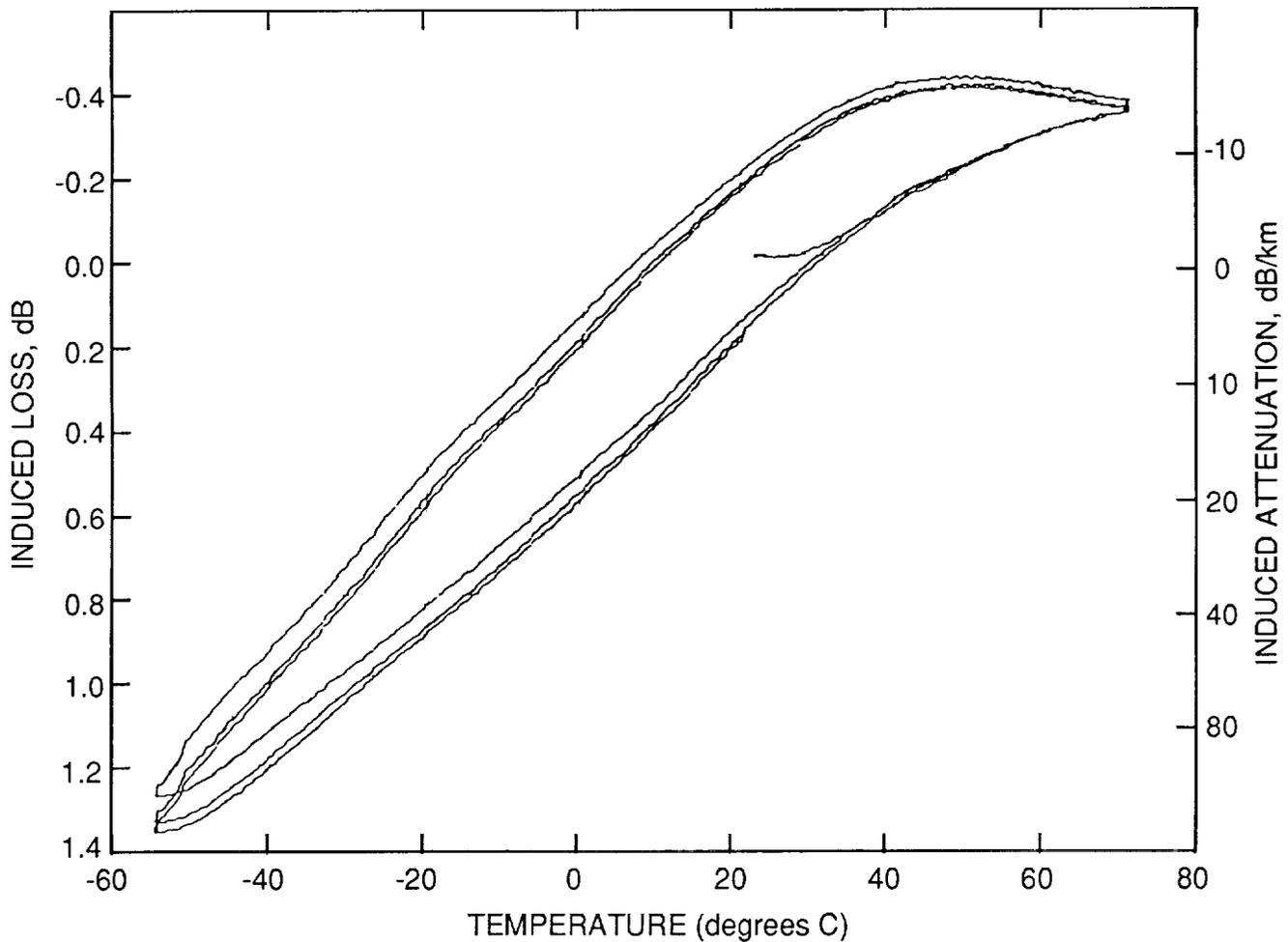


Figure 7. Temperature-induced loss for flight sample P-2, measured in September 1991.

The instrumental stability was improved significantly between the first and last tests. The pre-flight setup did not include stabilization of the LED power and was sensitive to room temperature. The stability was no better than 0.2 db. The latest instrumentation incorporated temperature stabilization of the electronics and compensation for changes in LED power and was stable to 0.01 db, possibly better if not disturbed.

We have assumed that the observed losses are distributed uniformly over the sample length, and that they can be described in terms of a loss per unit length (db/km). No measurements have been made during the temperature tests to verify this assumption, but no indication of non-uniform attenuation was found in our earlier OTDR tests. We feel that this assumption is a reasonable one.

The loss increment for the pre-flight test and the control sample are in agreement, and we feel the control sample data showing a change in loss of 23 db/km is the more reliable. The first post-flight test of the flight sample indicated a loss increment of 51 db/km and the subsequent multicyle test resulted in 1.65 db, or 63 db/km. Thus, there is a small, but probably not significant, increase between the two post-flight measurements of the flight sample, but a clear difference between the behavior of the control and flight sample. One other sample (C-6) showed similar behavior, but there was no clear difference between pre-flight and post-flight measurements for the other eight samples. The two samples showing the growth in temperature response were very poor performers under low temperature pre-flight. At this time, we are not able to explain these somewhat anomalous results in terms of the cabling configuration.

4.. ANALYSIS OF CONNECTOR CONTAMINATION

In the June 1991 LDEF Symposium, we reported that four of the twenty connector terminations had observable contamination on the polished end surface of the connector ferrule, although none of the foreign material appeared on the core area of any of the fibers. Since that time, we have subjected termination C-1b (from sample C-1), shown in Figure 8, to a more detailed analysis.

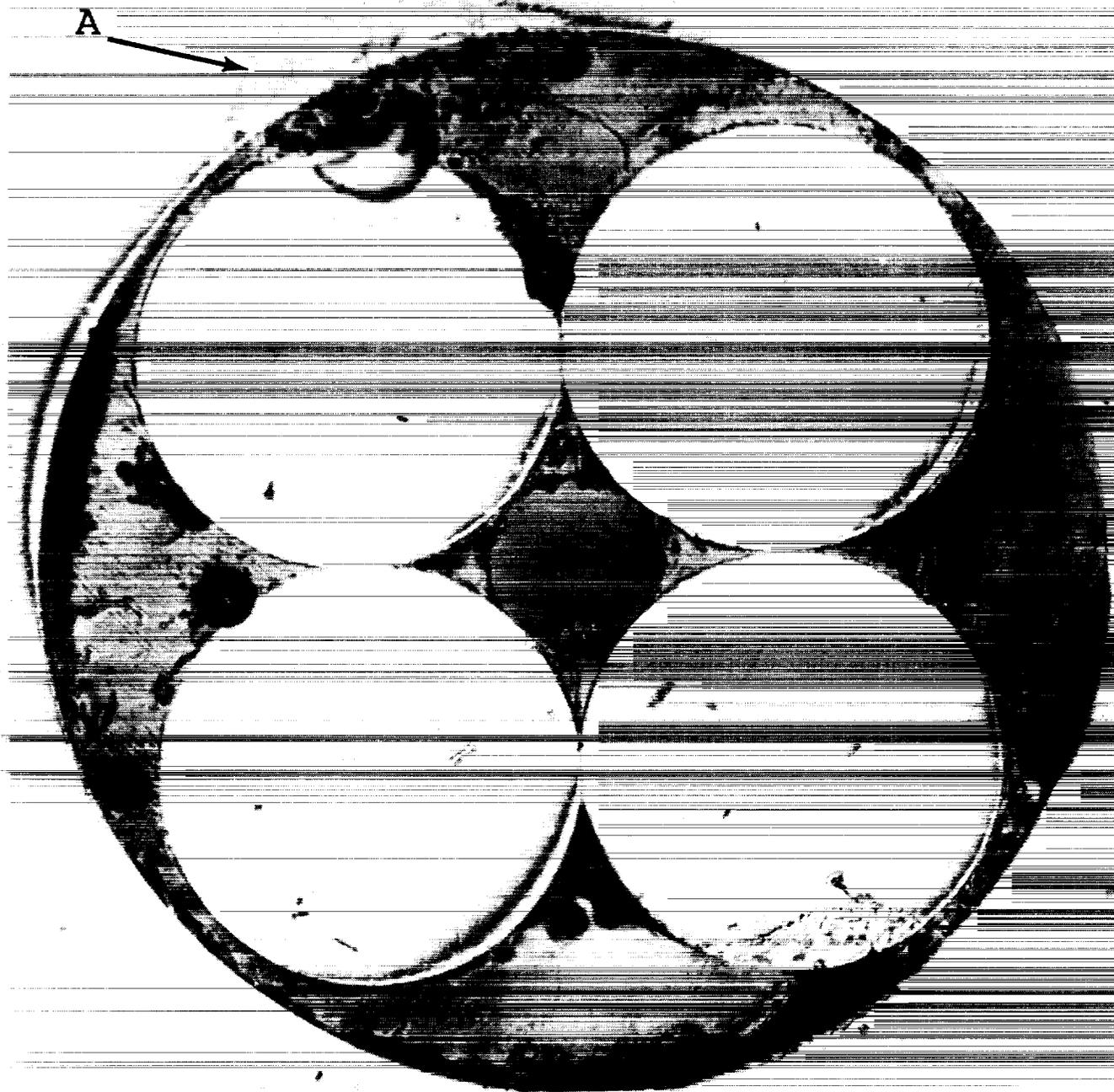


Figure 8. A photograph of termination C-1b showing deposit (A) which was determined to be epoxy material.

The visible contaminant near the outer edge of the locating pins in the ferrule was examined spectroscopically in the IR (footnote 2). A fourier transform IR spectrometer adapted with a microscope was used to observe the light reflected from a very small selected area of substrate. The focal spot could be made as small as several microns in diameter to examine a small particle of material on the substrate (the polished ferrule surface).

In the photograph, Figure 8, the particle marked "A" was found to be epoxy and aliphatic amine epoxy curing agent. The conclusion is that for this connector, the epoxy material used in the termination was not properly mixed or cured. It may be desirable to devise techniques for quality assurance in this area for future flight hardware.

The particles seen on termination C-3a, not shown, were found to be foreign particles, not derived from materials in the fiber cable or connector. Thus, at this point, two (of the 20) terminations show deposits which are felt to be derived from materials used in cables and connectors, one from an unsuitable jacket material and one from the epoxy used to make up the connector termination.

The other conclusions stated in the earlier paper remain valid:

- There was no measurable attenuation due to connector contamination.
- Mated connectors would have had lower probability of contamination.

5. CONCLUSIONS

Radiation damage to optical fibers is well known, and there has been a great deal of work on the subject, extending over many years. There has been significant progress toward developing rad hard fibers since the 1982 time frame when these fibers were made. Our best fiber, sample P-1, with a specific radiation-induced loss of about 2-3 db/km-krad, would have been adequate for many applications. However, fibers have recently been developed with orders of magnitude less responsive to low-dose rate long term radiation, particularly at 1.3 μm . Several fibers have been reported with less than 10^{-2} db/km-krad, the lowest reported value being 10^{-4} db/km-krad for a long-term low dose rate exposure (ref. 8).

However, the basis for extrapolating laboratory data on annealing, most of which extend only to 1 day (10^5 sec) and some to ~ 100 days is less firm, and the model is quite empirical in nature. Confirmation is needed that no annealing process is present with a long time constant, which may be overlooked when investigating the dominant short-term recovery. Our LDEF data, although not as accurate as we would like because of our short samples, lends support to the model used for extrapolation, at least out to 6 years. The hardest fibers appear to be those with pure fused silica cores, which have a short time constant for annealing. Fortunately, their rapid recovery facilitates measurement of the annealing curve with a short-term test.

Much less effort has been dedicated to understanding temperature induced loss in detail, and it is quite possible that there is no single mechanism to understand. Although we found that one sample performed well, even after the order of 3×10^4 temperature cycles in orbit, most of our samples exhibited more than 10 db/km excess loss over the -55° to $+70^\circ$ C range, and would not be suitable for a long exposed run. Some were much worse. More work and more testing at low temperature would be productive. The progressive change in temperature behavior seen in sample P-2 is a separate, but probably overlapping issue. Both effects are felt to be a function of buffering and cabling, both in materials and in configuration.

Our general conclusions to date are the following, with the conclusions from our earlier paper restated and included:

- All our LDEF samples were functional and, with a few exceptions, would have performed well in a properly designed spacecraft system.

- The observed radiation darkening for the LDEF samples was consistent with an extrapolation from a 2-day laboratory recovery test.
- Connectors performed well, but quality control of epoxy cements is needed.
- Low temperature extremes should be avoided.

Long runs, of the order of 1 km or more, or exposed cable runs will require a thorough understanding of:

- Radiation-induced loss and its subsequent recovery.
- Temperature effects on cables.
- Outgassing and aging effects from polymers in cables and connectors.
- Risk of damage from micrometeoroid impacts.

The importance of these issues depends strongly on the application, both in terms of the environment seen by the fiber optic components and of the system configuration (i.e. link length). In a small system, tens of meters in extent, there is little cause for concern because adequate design margins are available. However, if the system is long enough to be loss-limited, or if the radiation environment is severe enough, then the first two issues, radiation damage and temperature extremes, may be quite important. Polymer aging and micrometeoroids are second order issues. Protection of exposed cable from micrometeoroid impacts is desirable, but note that the LDEF experience does not prove that fiber cables are more susceptible to damage than copper wires of comparable size.

There is another issue arising if extreme low temperature operation of the fiber cable is a possibility. Annealing of radiation-induced loss is thermally driven, and does not occur at low temperature (e.g. -70°C). As a result, the long-term low dose rate attenuation coefficient could increase by 1-2 orders of magnitude if the fiber stays cold (ref .7). Intentional photobleaching may alleviate this problem, but design to avoid sustained temperatures much below room temperature is a preferable approach, if possible.

To summarize, the LDEF experience has indicated that fiber optics can function well in a spacecraft system, and the most important design issues are radiation and low temperature.

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FOOTNOTES

1. Sample P-1 was packaged in a Siecor type 144 cable.
2. Anderson, Mark: JPL internal memo, May 18, 1992.

